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THERMO-REMANENT MAGNETIZATION (TRM) OF Ni-Fe ALLOY

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Abstract: The changes of the direction and the intensity of the TRM of 5 atomic weight per cent (5 at%)~15at%Ni-Fe alloys have been measured after various heat treatments. The directions of TRM are stable. The intensities of TRM decrease by cooling in zero magnetic field. This decrease is due to the martensitic transformation from fcc phase to bcc phase which are discussed by comparing with the results of the Mössbauer effect.

1. Introduction

The Ni-Fe alloy is the original ferromagnetic substance of the natural remanent magnetization (NRM) of meteorites. Some of rock-forming minerals contain Ni-Fe alloys which transform martensitically from fcc phase to bcc phase (KAUFMAN and COHEN, 1958). In order to deduce the cosmic paleomagnetic field from RM of meteorites, it is very important to know whether or not the RM obtained in the temperature range from Curie temperature (T_c) to room temperature (T_0) is preserved in bcc phase after martensitic transformation. The martensitic transformation occurs in cooling below the martensitic transform point (T_{MS}), by rolling or grinding.

From the previous experiments of 20 at% ~29 at% Ni-Fe alloys (MOMOSE *et al.*, 1984; MOMOSE and NAGAI, 1985, 1986), the RM obtained by cooling from T_c to T_0 phenomenologically resemble each other in magnetic behavior as follows:

(i) TRM obtained by cooling at 77 K in geomagnetic field is stable, while TRM is broken by cooling in zero magnetic field.

(ii) The direction and the intensity of TRM obtained by cooling at 77 K in geomagnetic field are unchanged by the 2nd cooling in geomagnetic and zero magnetic fields.

The purpose of the present work is to investigate the magnetic properties of 5 at% ~15 at% Ni-Fe alloys by the same methods for the previously used alloys, where the martensitic transformation occurs above T_0.

2. Experimental Results and Discussion

2.1. 5 at% Ni-Fe alloy

The Mössbauer spectra of ^{57}Fe in 5 at% Ni-Fe alloy are shown in Fig. 1 in the case of various heat treatments.

Spectrum (a) is due to the powder sample which is obtained by grinding the alloy block into grain size of 90–200 μ in diameter and is in bcc phase (this sample is denoted

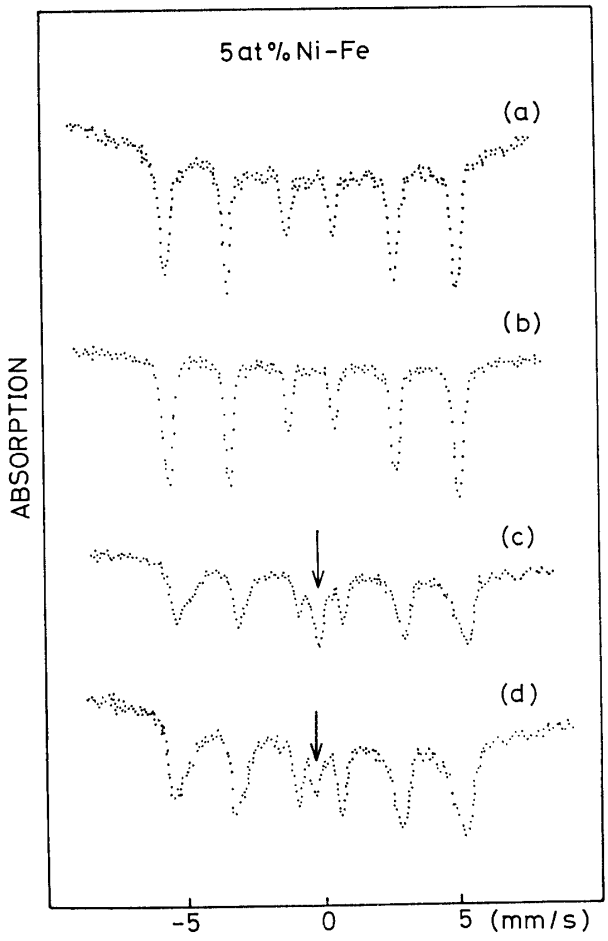

Fig. 1. The Mössbauer spectra of ^{57}Fe in 5 at% Ni-Fe alloy.
Spectrum (a): The original sample in bcc phase.
Spectrum (b): The sample annealed at 650°C and in bcc phase.
Spectrum (c): 15–20% fcc phase appears by annealing at 920°C (denoted by the arrow).
Spectrum (d): The amount of fcc phase decreases by the martensitic transformation after cooling at 77 K (denoted by the arrow).

by "original"). Spectrum (b) indicates that the sample annealed at 650°C for 1 h in vacuum of 10^{-3} Pa has no fcc phase since the phase transition point from bcc phase to fcc phase is about 770°C. On spectrum (c), fcc phase appears by the phase transition after annealing at 920°C for 1 h in vacuum of 10^{-3} Pa. The amount of the fcc phase is 15–20%. After cooling this sample at 77 K, spectrum (d) shows that fcc phase decreases by the martensitic transformation, where about 5% fcc phase remains.

The direction of the RM did not largely change by the heat treatment up to 920°C, while the intensity decreased 14% after cooling in zero magnetic field (see Table 1). This decrease results from the martensitic transformation (fcc→bcc) as shown in the Mössbauer spectra. The behaviors of RM in various heat treatments are plotted in Fig. 2.

2.2. *10 at% Ni-Fe alloy*

The Mössbauer spectra of ^{57}Fe in 10 at% Ni-Fe alloy are shown in Fig. 3. Spectrum (a) shows that the original powder sample ground from the alloy block is in bcc phase and has no fcc phase. Spectrum (b) indicates that the sample annealed at 700°C for 1 h in vacuum of 10^{-3} Pa has about 17% fcc phase. After cooling the sample of spectrum (b) at 77 K, fcc phase in the powder sample decreases from 17 to 8% by martensitic transformation and this fact is shown in spectrum (c).

Table 1. TRM of Ni-Fe alloys (powder) after cooling at 77 K in zero and geomagnetic fields. The declination of our laboratory is uncertain and the inclination is 57°.

Samples		Heat treatment	D	I	J ($\times 10^{-3}$ emu/g)	J/J_0
5 at%Ni-Fe	(A_0)	TRM (800°C, 10^{-3} Pa) bcc	−6.02°	47.79°	18.422	J_0
	(A_1)	cooled (A_0) at 77 K in parallel to geomag. field	−6.31°	49.00°	19.045	1.03
	(A_2)	2nd TRM (920°C, 10^{-3} Pa) bcc	−8.56°	58.59°	23.161	2nd J_0
	(A_3)	cooled (A_2) at 77 K in zero magnetic field	−4.98°	58.91°	20.034	0.865
10 at%Ni-Fe	(B_0)	TRM (700°C, 10^{-3} Pa) bcc	15.94°	57.48°	5.725	J_0
	(B_1)	cooled (B_0) at 77 K in zero magnetic field	37.47°	65.77°	3.263	0.570
	(B_2)	2nd TRM (700°C, 10^{-3} Pa) bcc	14.87°	65.75°	5.711	2nd J_0
	(B_3)	cooled (B_2) at 77 K in parallel to geomag. field	25.60°	68.91°	5.237	0.917
15 at%Ni-Fe	(C_0)	TRM (700°C, 10^{-3} Pa) bcc	3.10°	56.37°	9.670	J_0
	(C_1)	cooled (C_0) at 77 K in parallel to geomag. field	3.98°	57.00°	9.369	0.969
	(C_2)	cooled (C_1) at 77 K in zero magnetic field	4.30°	57.75°	8.117	0.840
	(C_3)	2nd TRM (700°C, 10^{-3} Pa) bcc	4.05°	55.41°	7.652	2nd J_0
	(C_4)	cooled (C_3) at 77 K in zero magnetic field	8.97°	53.68°	5.356	0.699

D=declination, I=inclination, J=intensity of magnetization, J_0=original intensity.

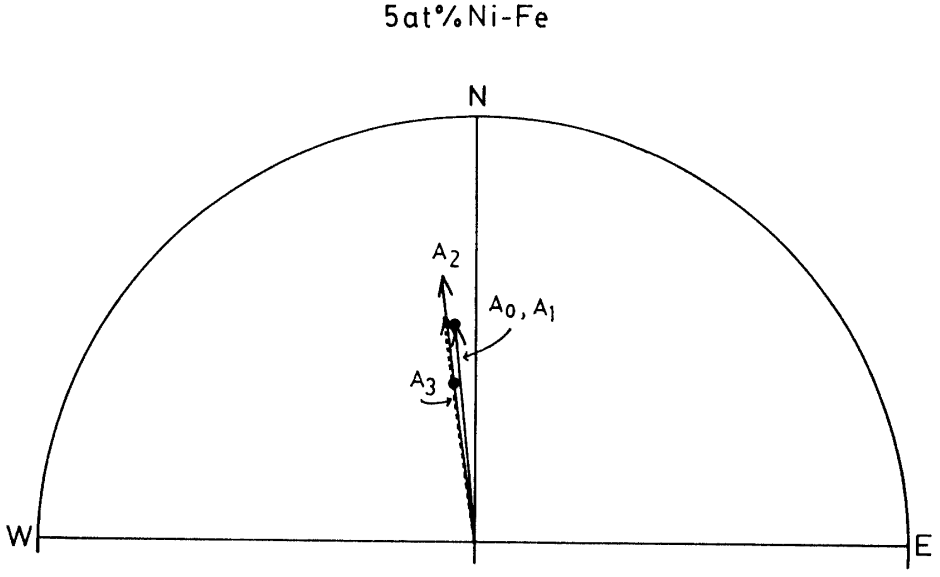

Fig. 2. The directions of RM of 5 at%Ni-Fe alloy. The arrow and the closed circle show the normalized intensity of magnetization and the magnetic direction point, respectively. A_0, A_1, A_2 and A_3 indicate the samples listed in Table 1.

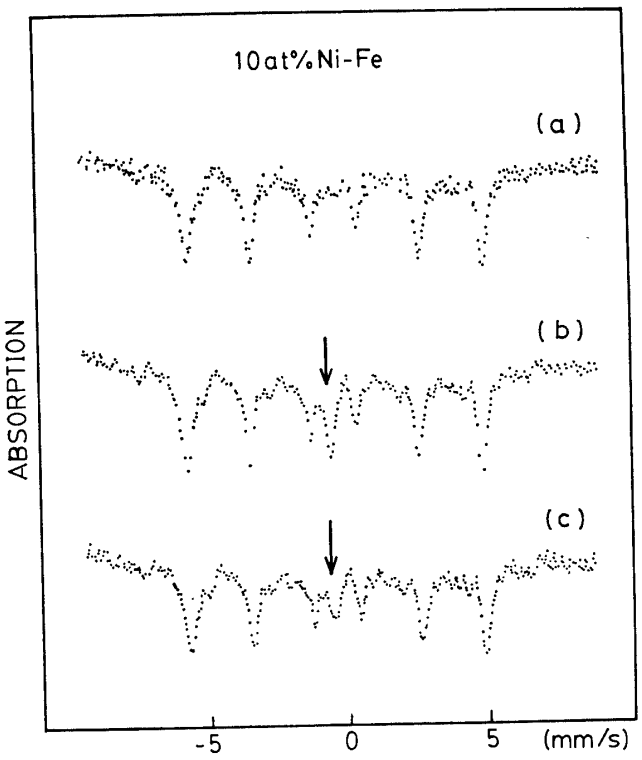

Fig. 3. The Mössbauer spectra of ^{57}Fe in 10 at% Ni-Fe alloy.
Spectrum (a): The original sample in bcc phase.
Spectrum (b): The sample annealed at 700°C. The arrow indicates the spectrum due to fcc phase.
Spectrum (c): The sample cooled at 77K after annealing at 700°C. The arrow indicates the spectrum due to fcc phase decreased by the martensitic transformation.

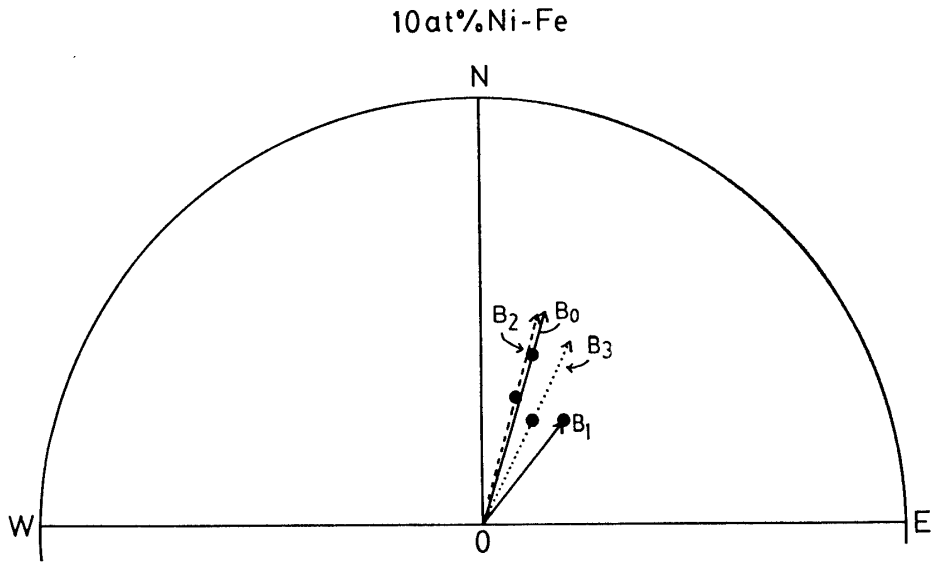

Fig. 4. The directions of RM of 10 at%Ni-Fe alloy. The arrow and the closed circle are same as Fig. 2. B_0, B_1, B_2 and B_3 indicate the samples listed in Table 1.

No increase of the intensity of RM was observed after cooling at 77 K in geomagnetic field. The change of the direction of RM was larger than those of 5 at% and 15 at%Ni-Fe alloys, but not so large as those of more than 20 at%Ni-Fe alloys. These phenomena originate in the martensitic transformation as shown in the Mössbauer spectra. The behaviors of RM in various heat treatments are plotted in Fig. 4 and listed in Table 1.

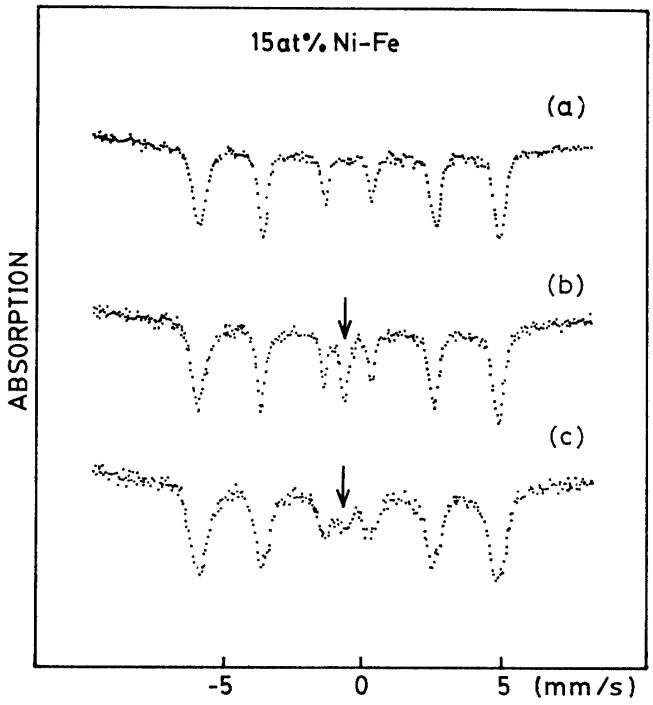

Fig. 5. The Mössbauer spectra of ^{57}Fe in 15 at% Ni-Fe alloy. Spectra (a)–(c) are same as Fig. 3.

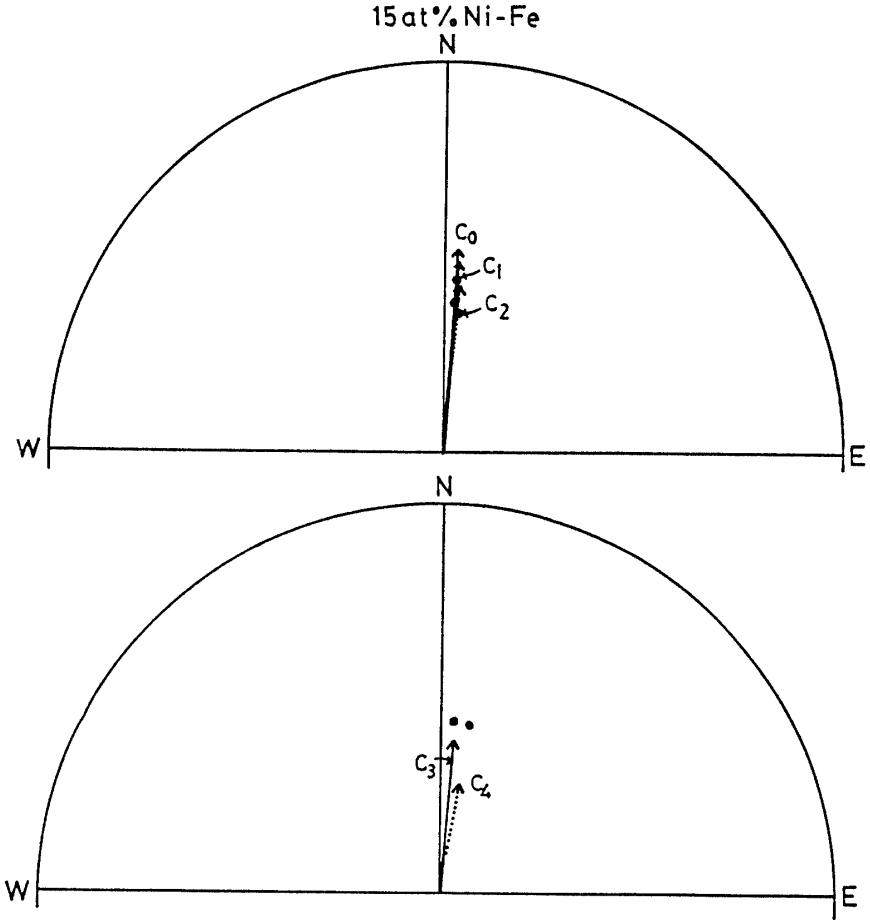

Fig. 6. The directions of RM of 15 at% Ni-Fe alloy. The arrow and the closed circle are same as Fig. 2. C_0, C_1, C_2, C_3 and C_4 indicate the samples listed in Table 1.

2.3. *15 at% Ni-Fe alloy*

The Mössbauer spectra of ^{57}Fe in 15 at% Ni-Fe alloy are shown in Fig. 5. Spectrum (a) shows that the powder sample is in bcc phase after grinding from the alloy block. Fcc phase appears after annealing at 700°C (spectrum (b)). After cooling at 77 K, the amount of fcc phase decreased by martensitic transformation as shown in spectrum (c).

The direction of RM cooled at 77 K in geomagnetic field was stable and unchanged by cooling in zero magnetic field ($C_1 \rightarrow C_2$). The intensity of RM was unchanged by cooling ($C_0 \rightarrow C_1$), while it decreased to 13% in magnitude in zero magnetic field ($C_1 \rightarrow C_2$) due to the martensitic transformation as shown in the Mössbauer spectra. These results are listed in Table 1 and plotted in Fig. 6.

The reason why the directions of RM in Figs. 2, 4 and 6 are not collinear with the direction of geomagnetic field is that the sample axis is not perfectly set in the direction of geomagnetic field in the electric furnace.

The feature of RM of 5 at% ~ 15 at% Ni-Fe alloys is that the intensity of RM after cooling at 77 K in geomagnetic field did not increase, while those of more than 20 at% Ni-Fe alloys increased more than 30%. The origins of the behaviors of RM after heat treatments are the existence of fcc phase at T_0 and the martensitic transformation from fcc phase to bcc phase. The directions of RM are stable, while those of more than 20 at% Ni-Fe alloys are changed by cooling at 77 K in zero magnetic field.

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